REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
6/30/96

3. REPORT TYPE AND DATES COVERED
Progress Report 5/20/95 - 6/1/96

4. TITLE AND SUBTITLE
Adaptive Dynamic Balance of Two and Four Legged Walking Robots

5. FUNDING NUMBERS
ARPA/ONR Grant
#N00014-95-1-1024

6. AUTHOR(S)
W. Thomas Miller, III

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical and Computer Engineering
The University of New Hampshire
Durham, New Hampshire 03824

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Thomas McKenna
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

19970513 039

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Two-legged and four-legged walking are the most versatile forms of land locomotion in the sense of maneuverability and the ability to traverse irregular terrain. Unfortunately, the problem of practical bipedal walking with dynamic balance has so far eluded solution using classical and other control techniques. We have been investigating the use of neural networks for on-line gait modulation during walking, using a 10 degree-of-freedom biped robot and a 20 degree-of-freedom quadruped robot developed in our laboratory. The research in the current project involves extending our adaptive walking control architecture, developed in prior research, to provide good performance over a wider range of stepping lengths and rates, and to provide good stability during both minor and significant deviations from nominal behavior. This should result in a truly practical control structure for walking with dynamic balance. This is a project progress report for the research carried our prior to June, 1996.

14. SUBJECT TERMS
Neural Networks, Robotics, Legged Locomotion

15. NUMBER OF PAGES
4

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Adaptive Dynamic Balance of Two and Four Legged Walking Robots

DARPA/ONR Grant #N00014-95-1-1024
5/20/95 - 12/31/96

W. Thomas Miller, III
Robotics Laboratory
Department of Electrical and Computer Engineering
The University of New Hampshire
Durham, New Hampshire 03824
(603) 862-1326 tom.miller@unh.edu
http://www.ece.unh.edu/robots/rbt_home.htm

PROGRESS REPORT: 6/30/96

Overview of progress on ONR-funded work over the past 12 months

The goal of this research is to develop strategies for the control of dynamic balance during two-legged and four-legged walking based on a hierarchy of simple gait oscillators, PID controllers and neural network learning, but requiring no detailed dynamic models. A common learning control architecture was developed for the UNH biped and quadruped robots which emphasized the use of multiple neural network learning modules to modulate on-line the outputs of simple gait generators. This feedforward control architecture proved to be successful at learning nominal dynamically balanced walking trajectories. However, it proved not to be robust. The control architecture was then modified by adding control elements for reacting to sensed disturbances and/or deviations from nominal behavior, patterned after results in the literature from human walking studies. The modified walking control architecture was refined in simulation, while an improved piezo-electric "vestibular system" was developed to provide better perception of body orientation. The modified walking control architecture is currently being implemented on the experimental biped and quadruped robots.

Adaptive Dynamic Balance of Two and Four Legged Walking Robots
(ARPA/ONR Grant #N00014-95-1-1024)

P.I.: W. Thomas Miller, III
The University of New Hampshire

Major accomplishment of ONR-funded work over the past 12 months

Two-legged and four-legged walking are the most versatile forms of land locomotion in the sense of maneuverability and the ability to traverse irregular terrain. Even in human designed spaces with horizontal floors and regular geometries, legged locomotion is more versatile than wheeled locomotion. Unfortunately, the problems of practical bipedal and quadrupedal walking with dynamic balance have so far eluded solution using classical and other control techniques. Statically unstable but dynamically stable legged locomotion is difficult because sensed states of balance or imbalance are related in complex ways to the recent history of prior control actions. In addition, once a state of imbalance is sensed reliably it is often too late to recover. Successful walking primarily requires doing the right thing to begin with (accurate feedforward control), while using closed loop reactive control mainly for minor gait adjustments, and using occasional predetermined recovery motions triggered by sensory events which are predictive of subsequent imbalance.

In general, biped walking with dynamic balance can be separated into three operating regions based on the duration of the single support phase (one foot on the ground) during each step. Similar considerations apply to quadruped walking if more than one foot is lifted simultaneously. If the single support phase is short relative to the time constant of the effective "inverted pendulum" (the true dynamics are clearly more complicated than those of a simple inverted pendulum due to the distributed mass in the multi-jointed structure), dynamic balance is relatively easy in that the biped doesn't have time to fall during the interval in which one foot is off of the ground. Single support duration is easily regulated by rapidly retracting and then extending the lifted leg. Balance is mostly a function of where the lifted foot is placed over sequences of steps and is rather insensitive to the details of the biped motion while a foot is lifted. This, in fact, is the problem addressed quite successfully by Raibert's work with hopping robots. Such a gait, however, is generally not smooth or energy efficient (similar to a person constantly jogging, independent of desired speed of locomotion).

If the single support duration is similar in magnitude to the time constant of the effective "inverted pendulum" (on the order of 0.4 seconds for our biped) dynamic balance becomes more difficult. After a foot is lifted the biped "falls" back onto the lifted foot, terminating the single support phase in accordance with the time constant of the system and the initial conditions (structural configuration and inertia) before the foot was lifted. The detailed motions of the biped structure thus affect the elapsed time before the biped falls back onto the lifted foot. The detailed motions of the biped must be adapted to match the effective time constant of the structure to the desired single support duration,

while preserving body momentum during the double support phase in order to ensure a smooth transition from one step to the next. This is the problem which has received the majority of our attention during the last year, with good results.

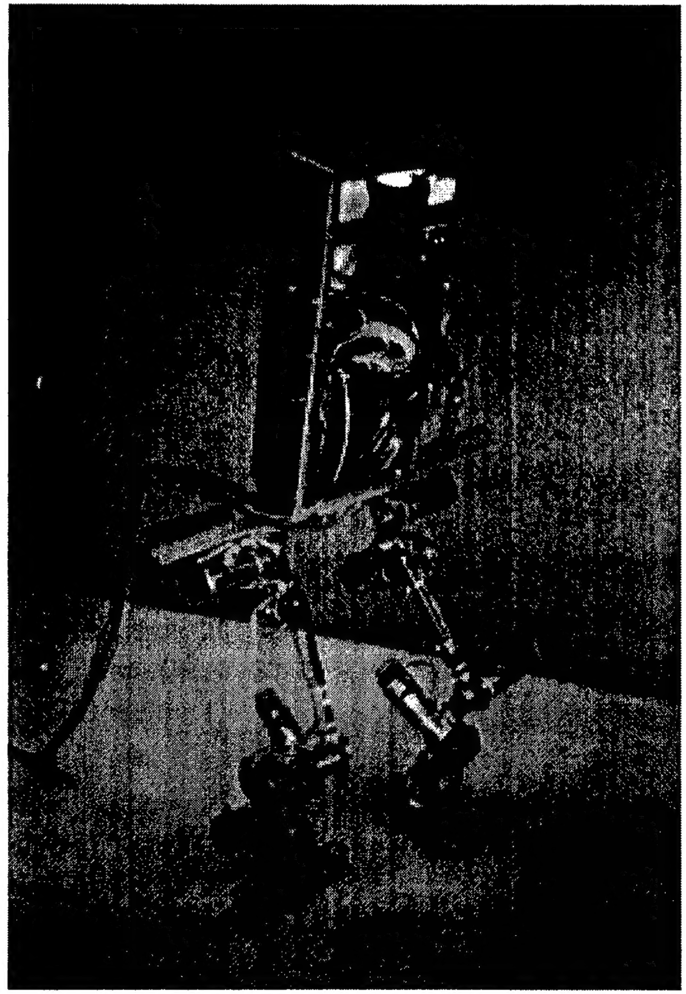
Finally, if the desired single support duration is long relative to the effective time constant of the system, the biped must be controlled by launching into and maintaining a state of quasi-static balance during the single support phase. This is extremely difficult since achieving a reasonable stride length requires that the biped undergo a substantial change in configuration (and redistribution of mass and momentum) during single support. The structure must be balanced precisely at every control cycle during this motion.

We have been investigating the use of neural networks for on-line gait modulation during walking, using a 10 degree-of-freedom biped robot and a 20 degree-of-freedom quadruped robot developed in our laboratory. For sensing balance, these robots are equipped with foot force sensors (4 per foot) and piezo-electric "vestibular systems" which produce a perceived body orientation by combining information from linear accelerometers and angular rate gyroscopes. The approach to walking control that we are studying is to use simple walking gait generators based on approximate kinematics of the structure to create repetitive walking motions. These simple walking patterns are then modulated by multiple neural network modules trained on-line, utilizing concepts of both supervised and reinforcement learning, to avoid states of sensed imbalance. Results to date indicate that our approach to on-line gait adaptation is effective at automatically developing the detailed nominal motions of dynamically balanced, phase-locked, feedforward gaits for two-legged and four-legged robots under nominal operating conditions, requiring very little a priori knowledge of the robot dynamics.

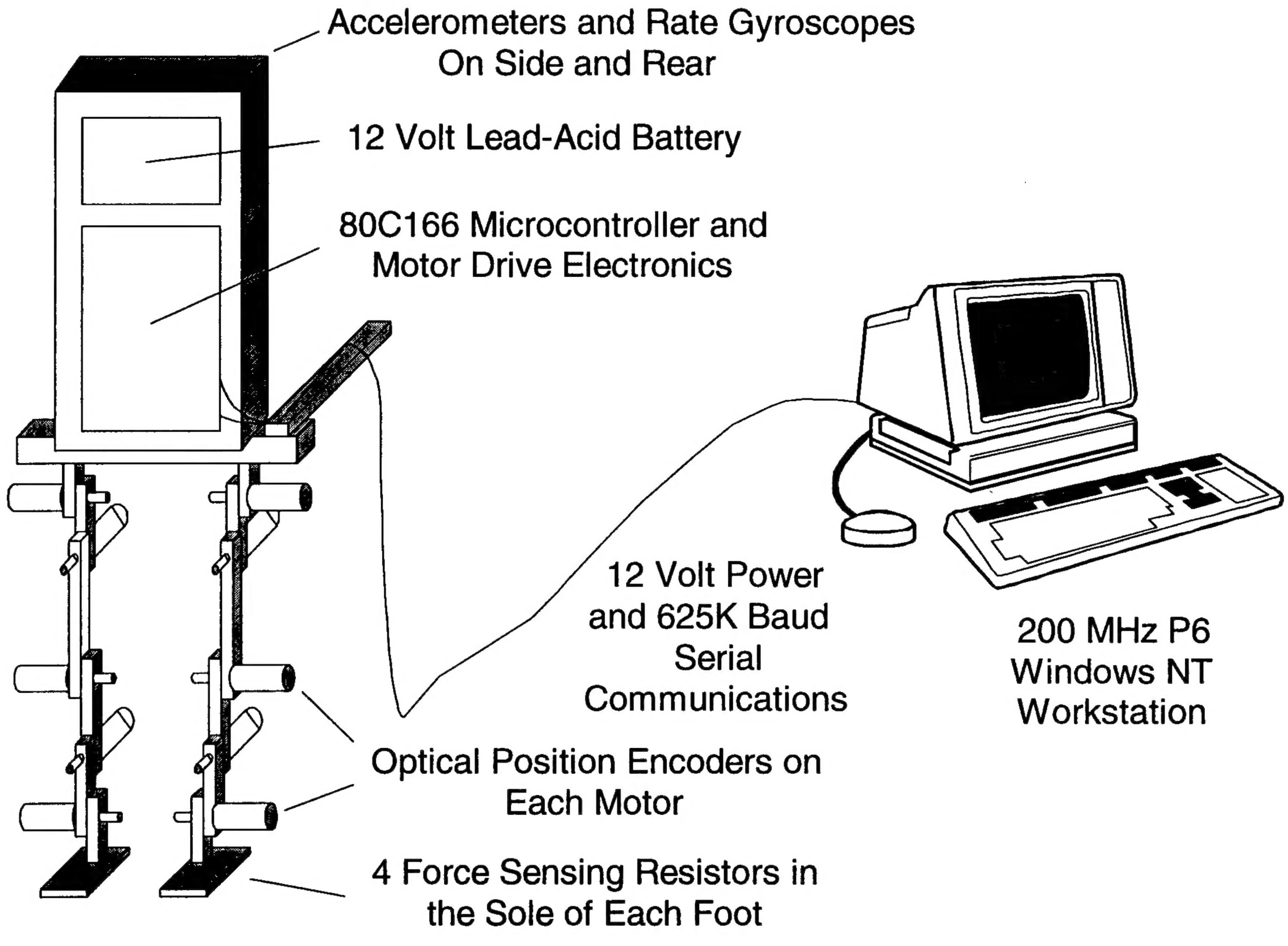
Since our initial control architecture depended nearly exclusively on learned feedforward it proved not to be robust, limiting overall performance. Deviations from the learned nominal behavior would inevitably occur, accumulating to the point of failure for more challenging gaits. Most recently, the primary goal of our research has been to increase the robustness of the walking control by adding control elements for reacting to sensed disturbances and/or deviations from nominal behavior. Studies reported in the literature suggest that two mechanisms may be used for this purpose in human standing and walking (although the details are not complete). Small disturbances are possibly handled by relatively high bandwidth reactive control of ankle torque based on vestibular and proprioceptive feedback. Larger disturbances are possibly handled by lower bandwidth changes in body posture involving the ankle, knee and hip joints. These corrective motions appear to be triggered by sensory events (again from the proprioceptive and vestibular systems) but are largely feedforward in nature subsequent to the initial trigger.

We have successfully integrated similar control strategies into the controller for our biped simulator and have used the simulator to refine details which are poorly defined in the available literature from human studies. In addition we have developed an

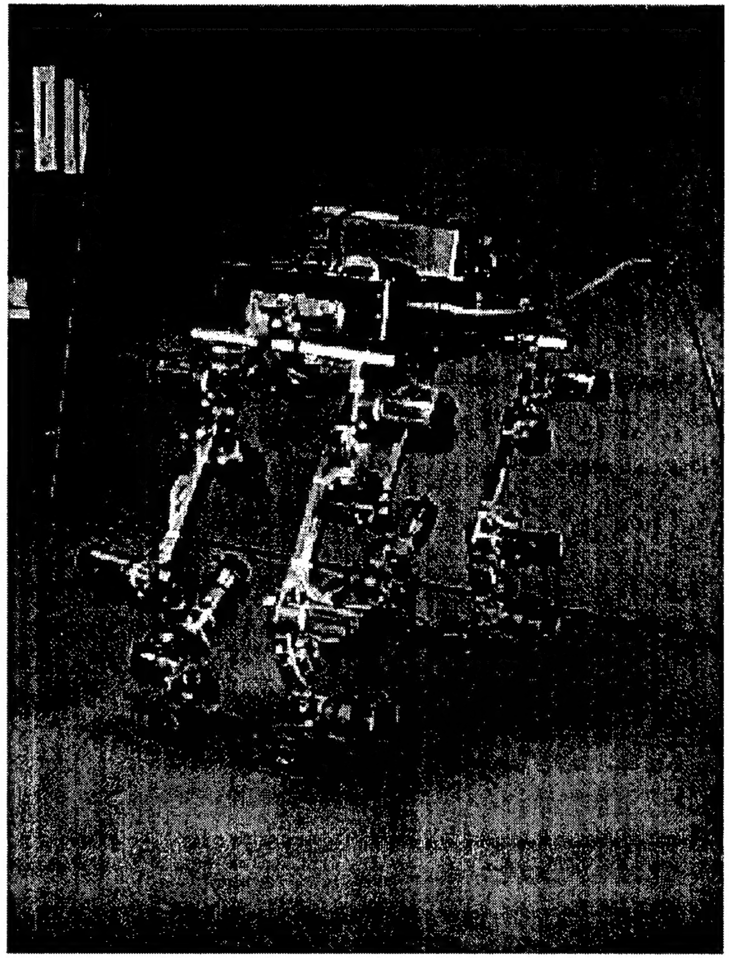
improved piezo-electric "vestibular system" for the experimental robots providing a continuous perceived body orientation using a combination of linear accelerometers and angular rate gyroscopes. Finally, we are upgrading the control software for our experimental biped and quadruped walking robots in order to study experimentally the robustness properties of the control combining learned feedforward gaits, reactive ankle torque control about the learned nominal gait trajectories, and preprogrammed disturbance rejection (balance recovery).



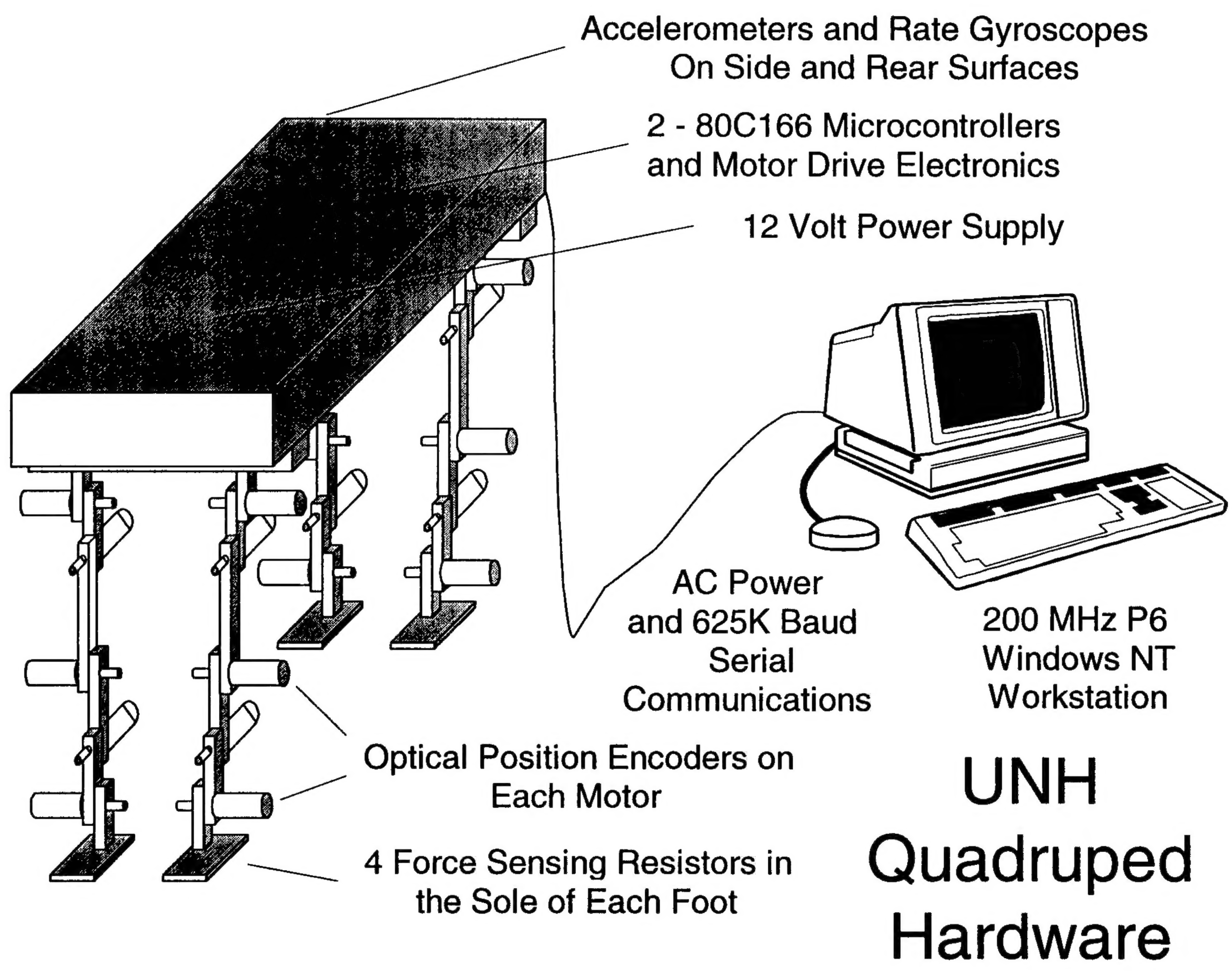
The UNH biped robot.



UNH experimental biped system.



The UNH quadruped robot.



UNH experimental quadruped system.